GOATS 2014
Adaptive and Collaborative Exploitation of 3-Dimensional Environmental Acoustics in Distributed Undersea Networks

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LONG-TERM GOALS

To develop net-centric, autonomous underwater vehicle sensing concepts for littoral MCM and ASW, exploiting collaborative and environmentally adaptive, bi- and multi-static, passive and active sonar configurations for concurrent detection, classification and localization of subsea and bottom objects..

OBJECTIVES

The overall objective of the continued research is to further research and develop the *Nested Autonomy* concept, based on fully autonomous, *Integrated Sensing, Modeling and Control* for undersea networks with limited and intermittent communication connectivity, developed under the past GOATS program. In this phase, we will focus on assessing and understanding the spatial diversity of strongly 3D acoustic environments, including both signal and noise.

SA core objective is to identify features of the 3D scattering by seabed objects which can form the basis for robust classification, and in turn develop an autonomous classification approach which combines bistatic sensing with machine learning and behavior-based autonomy, which is sufficiently efficient and robust for autonomous use within the constraints of the available computational resources on today's underwater vehicles. The long term object of the research into the use of the SVMs target classification is to develop SVM model generation processes and AUV behaviors by which a vehicle with the appropriate model on board would be able to confidently identify characteristics of localized targets based only on the hydrophone-sampled bistatic scattering amplitudes collected in one or two passes around a target. The end goal would be to have multiple AUVs in a target field able to work collaboratively to classify targets by acting as sources or sensors around different targets. In the nearer term, the primary goals for

SVM target classification are to examine the combination of machine learning with adaptive AUV behaviors to be able to classify spherical and cylindrical targets by shape in a bistatic scattering field. This includes using simulation to develop and test SVM training, testing, and path optimization algorithms, as well as the adaptive waypoint behaviors required by this approach, with validation through field experiments of opportunity.

APPROACH

The fundamental approach of GOATS is the development of the concept of a network of AUVs as an array of *Virtual Sensors*, operating with a common MOOS-IvP Payload Autonomy architecture, with fully *integrated sensing, modeling and control*. This autonomy-centric *Nested Autonomy* control paradigm significantly reduces the inter-platform communication requirement to be consistent with the low bandwidth/high latency reality of shallow water acoustic communication.

The *Nested Autonomy* paradigm with MOOS-IvP for operating undersea networks with extremely limited communication connectivity, developed under GOATS, has been transitioned into several other ONR, NSF, and DARPA programs. As in the past GOATS effort, MIT is utilizing the open-source MOOS-IvP autonomy software infrastructure software originally developed under funding from ONR (MOOS by Code 32, and IvP by Code 31).

A cornerstone of the research, in addition to the field demonstrations, will be the use of the unique MIT *Nested Autonomy Simulation Environment,* developed under the past GOATS effort, and applied extensively in other programs, such as SWAMSI, ASAP, PLUSNet, and currently the DARPA DSOP program. Centered around the MOOS simulator, it provides a powerful testbed for nested, autonomous systems. Being fully linked to the MSEAS (earlier HOPS) ocean prediction system and the SEALAB high-fidelity acoustic simulator, this simulator provides a unique capability for the development of distributed, autonomous systems for passive and active acoustic surveillance in the littoral, providing a powerful testbed for the development of new environmentally and tactically adaptive sonar sensing.

The development of GOATS concepts is based heavily on simulation, incorporating and integrating high-fidelity acoustic modeling, platform dynamics and network communication and control. In regard to the environmental acoustic modeling, MIT continues to develop the OASES-3d modeling framework for target scattering and reverberation in shallow ocean waveguides. As was previously the case for the MCM effort, the approach has been to develop a complete system simulation capability, where complex adaptive and collaborative sensing missions can be simulated using state-of-the-art, high-fidelity acoustic models for generating synthetic sensor signals in real time. This is being achieved by linking the real-time MOOS simulator with a generic, high-fidelity acoustic simulation framework GRAM, which in 'real-time' generates element-level time-series using Green's functions using legacy environmental acoustic models such as OASES, KRAKEN and BELLHOP.

WORK COMPLETED

Autonomous Characterization of Underwater Targets from Bistatic Scattering

The goal of this research is to develop an AUV payload and methodology that uses 3D bistatic

acoustic scattering data collected by a simple hydrophone nose array to perform real-time target classification and parameter estimation. In this paradigm, a fixed acoustic source (ship-based or rail mounted) is used to insonify the target/targets. An AUV or multiple AUVs with simple hydrophone arrays use collected acoustic data to first localize seabed targets, then characterize
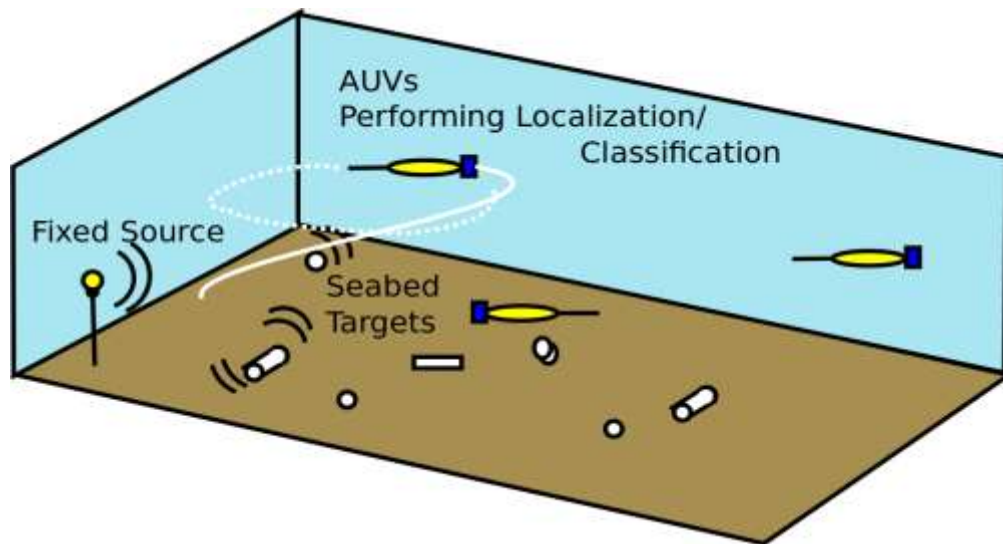
them in real time based on bistatic scattering amplitudes (Fig. A).

Figure A: AUVs sample bistatic scattering fields around targets insonified by a fixed source.

Two bistatic scattering experiments were conducted to demonstrate this concept on simple spherical and cylindrical targets. The first was in May 2014, and resulted in full bistatic scattering data sets from spherical and cylindrical targets. The data was compared to simulation results, and used to train and test machine learning classification models. A November 2014 scattering experiment in Massachusetts Bay was used to demonstrate estimation of orientation of an aspect dependent target using scattering amplitude data calculated in real time.

The proof-of-concept demonstration conducted over the last year based on the data from the two experiments hinged on three components: the target characterization methodology, experimental data collection, and testing of the methodology with simulation and real data.

Classification and Regression Methodology

A combination of signal processing and machine learning is used to go from array data to target classification or a regression estimate of target orientation. The acoustic scattered amplitudes were either simulated using the OASES-SCATT acoustic package or calculated from real data collected by the AUV *Unicorn* on a 16-element, 0.5m spaced nose array. The bistatic angle of each amplitude value is used to map the sampling location to a feature number using a bistatic angle bin size.

The training process takes in feature-mapped acoustic amplitude data and generates training, validation and testing example sets using that data. A Support Vector Machine (SVM) is then used to train a model for classifying new target data for the sphere versus cylinder classification, or for estimating target orientation for target aspect regression. The validation set is used to select SVM model parameters and sampling characteristics. Analysis of the independent test sets is used to assess model performance and create a confidence model.

A vehicle loaded with the results from the training/analysis process is then able to characterize underwater targets using a combination of vehicle behaviors, signal processing and machine learning classification or regression. Once a target track is sufficiently confident, the target characterization behavior and processing chain are initialized. The target characterization behavior provides the vehicle with a path that keeps the array broadside to the target. While it follows this path, a classification or regression processing chain calculates target scattering amplitude. The list of feature-mapped target amplitudes are used to classify the target or estimate target orientation. This process continues until a confidence threshold is reached. Testing has been carried out using the LAMSS MOOS-IvP simulation environment, using scattering amplitudes derived from acoustic simulations.

Vehicle Payload for Collecting High-quality Bistatic acoustic data

The success of the two scattering experiments was contingent on a precision data acquisition payload developed in 2014 for the AUV *Unicorn*. Precision timing was required for bistatic data collection because the source and vehicle are not co-located, and GPS-based timing is unavailable underwater. Array data was recorded using a pair of General Standard Corporation 24DSI12-PLL analog to digital conversion boards, triggered using a GPS-synchronized MicroSemi Chip Scale Atomic Clock (CSAC). The final calibrated data acquisition system was determined to have an arrival time error of less than 21.3us with 95% confidence, and a phase error of less than 8.07 ns with 99% confidence. That amount of arrival error results in less than 0.04m range error.

Good navigation and adaptive autonomy were also critical for success in experiment. The navigational drift with current instrumentation was between 0.3% and 0.5% of the distance traveled between GPS fixes. The vehicle surfaced for GPS every 10 minutes to prevent drift from accumulating significantly.

Summary of GOATS'14 Experiment- Adaptive and Collaborative Exploitation of 3D Environmental Acoustics

The GOATS'14 Experiment was conducted on May 21, 2014 as a part of the BayEx'14 experiment in St. Andrews Bay near Panama City, FL. An acoustic source was fired each second, triggered by GPS Pulse Per Second (PPS) signal, using a 7-9kHz LFM chirp. A spherical target and a cylindrical target were deployed approximately 60m from the source location. The AUV *Unicorn*, fitted with a 16-element nose array with 0.05m spacing and the acoustic payload described above, was used to collect acoustic data around the two target types. The final data sets included 2162 usable scattering data files around the sphere and 3432 usable scattering data files around the cylinder.

Massachusetts Bay Scattering Experiment

On November 10, 2014 a second bistatic scattering experiment was conducted in Broad Sound of Massachusetts Bay using the AUV *Unicorn*, a 147dB omnidirectional Lubell source, and an open-ended steel pipe target deployed off of the R/V *Resolution*. The goal of this experiment was to collect bistatic scattering data sets around an aspect dependent target at different orientations. The collected data sets were then used to estimate target aspect relative to the source based on a simulation model.

The BayEx'14 experiment was highly controlled: the source and target locations were precisely know, the target was within 60 m of the high-power, directional source, and environmental factors were known ahead of time. In contrast, this experiment used a ship-based, low-power omnidirectional source approximately 100 m from the target. There was large uncertainty in target location as it was dropped of the back of the ship, and the target orientation was completely unknown. The environment, including bottom type, could be guessed at but was not measured during the experiment. One of the goals of this experiment was to show that the methodology demonstrated in BayEx'14 would work in a more challenging environment.

The configuration for this experiment is shown in Figure B. The ship was first anchored to the north of the target to collect a null data set and bistatic data for the first target aspect. The ship was then moved to the south and west of the target to collect bistatic data for the second target aspect. The part of broad sound used for this experiment most likely has a sand bottom and was between 15 and 18 meters deep while we were collecting data.
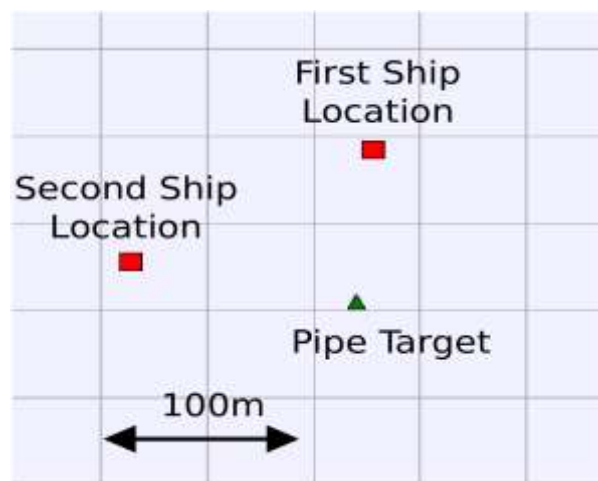

Figure B: Configuration for Massachusetts Bay experiment, including source and target positions. The R/V *Resolution,* with the Lubell source deployed at 3m depth, was first anchored about 100m north of the target, then moved to approximately 100m west of the target.

The 1.5 foot diameter, 5 foot long steel pipe target (Figure C) was dropped at an approximate local coordinate position of (x,y)=(170,155). The location was estimated using ship position when the target was dropped, but was only accurate within 10-15m. The orientation of the target was unknown.

Figure C: Open-ended steel pipe used as a target during the Massachusetts Bay experiment, sitting on the deck of the R/V *Resolution*. The pipe is 1.5 feet in diameter and 5 feet long.

A Lubell 916 acoustic source was used to insonify the steel pipe from the ship. The Lubell source is an omnidirectional underwater speaker capable of outputting 200Hz-20kHz in frequency. The source level was calculated as 147dB for this experiment. It was deployed at 3m depth off of the bow of the R/V *Resolution*. The source was fired at the start of each second using a software triggering system based on a MicroSemi SA.45 Chip Scale Atomic Clock (CSAC) Pulse Per Second (PPS) signal. The CSAC PPS signal was synchronized to GPS PPS, such that the 10ms, 7-9kHz chirp was played from the Lubell at the beginning of each second. Characterization of this system showed that it fired within 5ms of the start-of-second PPS signal. The jitter in firing was caused by the USB-to-Serial converter used to communicate with the CSAC.

Figure D shows the AUV sampling, ship and target locations for the three data collection sequences: two target aspects and sampling about a location with no target (null sampling). Our estimate of the actual target location changed as the experiment continued, so that the vehicle was given a sampling center progressively further north over the course of the experiment.
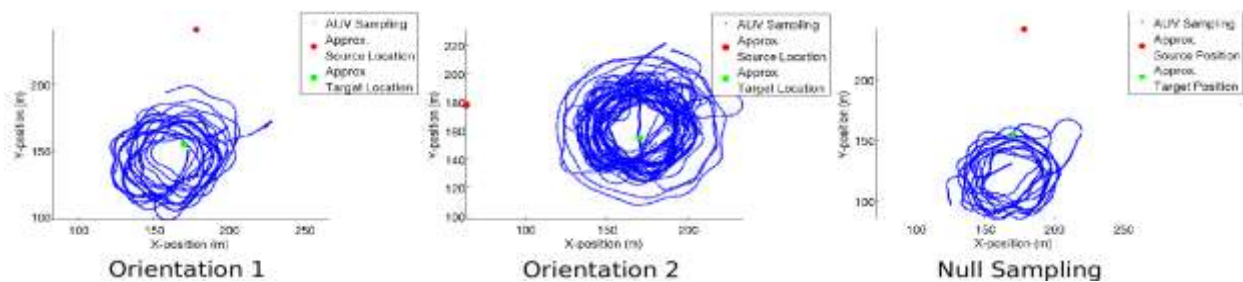

Figure D: Sampling during the Massachusetts Bay experiment for the two target orientation and null target data sets.

One of the data acquisition boards malfunctioned during data collection, so only the first 8 hydrophones could be used for data processing. This was not a major impediment to characterizing the radiation pattern from the two target aspects, as there was still enough resolution and aperture to distinguish the target contact. In total, 2065 usable acoustic amplitudes were collected about the first target aspect and 4363 about the second target aspect.

A moderately dense grid was collected from depths of 3 to 7 meters and from radii of approximately 15 to 40m to each target. Target location uncertainty means that the exact radii to the target were unknown, so there is some variation in this between the sampling for the two target aspects.

Simulation of Massachusetts Bay Experiment Target and Conditions

Real data was not available for the full range of possible aspect angles, so it was decided to train a regression model on simulation data. Scattering simulations were run in OASES-SCATT for a water-filled cylinder matching the dimensions of the cylinder in the experiment, 5 feet long by 1.5 feet diameter, in a 15m deep waveguide with a sound-speed of 1500 m/s and a fluid sand bottom. The source was approximated as 8kHz with a range of 100m to the target and a depth of 3m. Cylinder aspects in 5 degree increments were used from 0 to 180 degrees.

Training a Regression Model

A model for estimating target aspect was trained on the simulated scattering data using Support Vector Machine (SVM) regression. In this method, a model is trained using labelled data represented in a particular feature space. That model can then be used to estimate parameters from new data. Virtual AUV paths were used to sample the simulated data. The sampled data were converted into example vectors by mapping the bistatic angle of each sample to a feature bin, with each feature bin representing a range of bistatic angles. Each example vector was labelled with the aspect angle associated with the sampled scattered field. The resulting training set of example vectors was used to train a regression model. The regression model was then used to estimate aspect angle from data collected in the experiment.

Estimating parameters from real data

The scattering data collected during the experiment was first converted into example vectors by taking N sequential data points from the sampled data at a time. If the set of amplitudes designated for conversion into example vectors is represented by $A=[(\theta_0, A_0),(\theta_1, A_1),...(\theta_M, A_M)]$, the first example would be created using the data $[(\theta_0, A_0),(\theta_1, A_1),...(\theta_N, A_N)]$ and the second example would be created using the data $[(\theta_1, A_1),...(\theta_{N+1}, A_{N+1})]$ This process is repeated until $N+1=M$. The value of N was varied to assess the impact of the quantity of data collected on the quality of the angle estimate. The simulation-trained SVM regression model was used to estimate the orientation of the target using this data.

RESULTS

Analysis of GOATS'14 data

The bistatic acoustic scattering amplitudes, calculated from the acoustic data files collected around spherical and cylindrical targets, form a clear picture of the scattering patterns produced from those two targets types. The resulting maps can be used for comparison with the OASES-SCATT simulation environment, for assessment of the quality of both the experimental data collection and the simulation model. Figure E shows a comparison of normalized scattering amplitudes from the real experiment and OASES-SCATT simulation for depths from 2.5 to 3.5m.
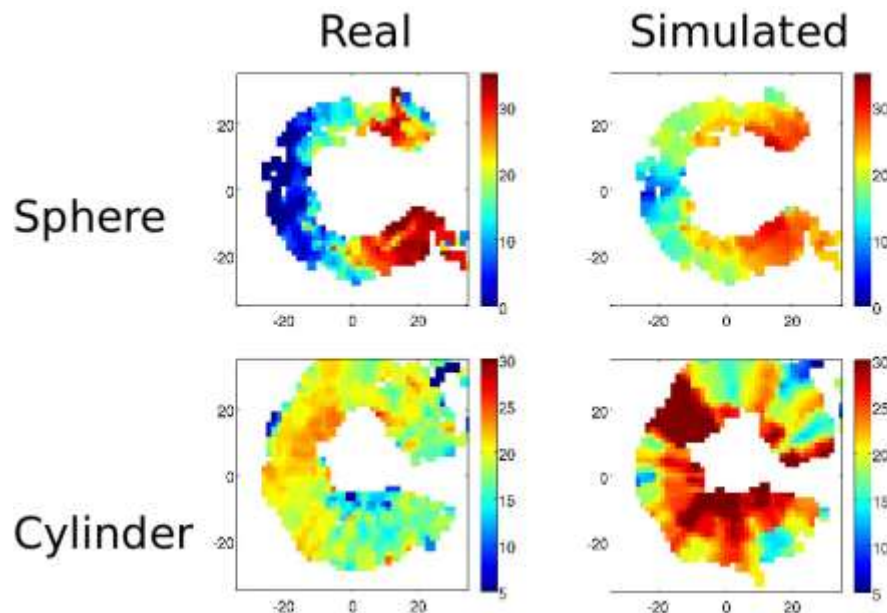

Figure E: Normalized real and simulated scattering amplitudes around spherical and cylindrical targets for depths of 2.5 m to 3.5 m.

The sphere real data set shows nearly identical locations of maxima and minima to the simulation. Important features appear in common to both simulation and real models, such as the +/-150 maxima and the general pattern from forward to backwards scattering directions. The cylinder simulation is less similar to the real data, though general location of minima and maxima are consistent between the model and the real data. The most obvious difference between the patterns is the greater backscatter intensity in the real cylinder's scattered field relative to the forward scatter intensity. This difference is caused by elastic effects not properly simulated with the rigid cylinder model used.

Two models were used to test the classification methodology on the GOATS'14 data. The first was trained based on the real bistatic data, the second on simulation data matched to the environment of the experiment. The accuracy from classification of real data using these models was highly dependent on the sampling duration. A plot of accuracy versus number of samples N is shown in Figure F for real and simulated models. Overall, the SVM model was very effective for classifying independent test example vectors once the vehicle had completed at least one full circle around the target. With two complete circles of the target, the accuracy of the

classification model in classifying new test examples reached 100%. The performance at different values of *N* and estimated confidence as real scattering data is collected would be used to inform vehicle behaviors during classification. The classification results for the real test examples were very similar using the simulated-data-based model and the real-data-based model. These results suggest that, at least for simple targets, a simulation approach could be used to augment real data in constructing SVM models used to classify targets in new environments.
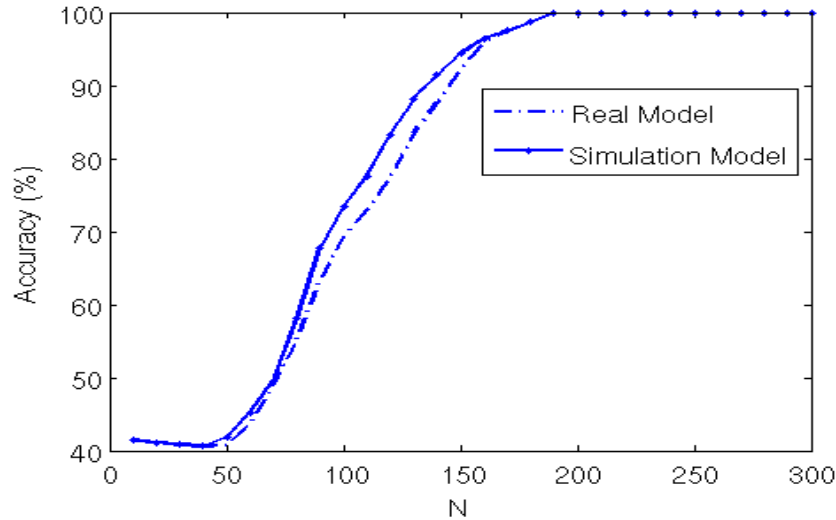

Figure F: Accuracy versus number of samples for classification of real data using simulation and real data-based models.

Real-time simulation

The use of real and simulated models for real-time classification was tested in simulation. Simulation studies and bench tests with the vehicle computer show the full processing chain successfully completing each second: it takes approximately 0.3 s to calculate the target amplitude from an acoustic file, the incorporation of acoustic data into the existing SVM example for classification takes less than 0.05 s, and the actual classification, which is only run when the vehicle exits a feature (every 5-10 seconds depending on range to the target), takes less than 0.5s. This shows the plausibility of using this method for real-time analysis and classification. These numbers were shown on the bench with the *Unicorn* computer when only the classification processing chain was running. Adding the target localization processing chain increased processing times significantly so that the acoustic data was fully processed only once every 3 seconds instead of every second.

Conclusions

Classification of spherical versus cylindrical targets using scattering amplitude data collected by an AUV was successfully demonstrated using real and simulated target scattering data based on the GOATS'14 experiment. Furthermore, it was shown in simulation on the bench that all

processes required for target classification using this methodology can be run in less than a second, which means AUV-based real-time classification and confidence estimation are plausible. While the sphere versus cylinder classification investigated here is a simplification of the target geometries of interest in mine countermeasures, this research shows the potential of the combination of sensing bistatic scattering fields with a linear array payload and applying machine learning classification of calculated acoustic amplitudes for solving the real-time target classification problem.

Massachusetts Bay Experiment

The Massachusetts Bay Experiment achieved the following objectives:

1. Collect bistatic scattering data for two aspects of a cylindrical target
2. Collect a bistatic scattering data set for a bottom location where no target was present
3. Demonstrate machine learning regression methodology using simulation-generated model to estimate aspect angle from real scattering data
4. Demonstrate real-time path planning on an AUV

Collected Scattering Data

The amplitude grid for the two aspects, orientation 1 and orientation 2, are shown in Figure G along with the amplitude grid for no target. The maps for both target orientations show radiation patterns that are primarily dependent on bistatic angle.

The bistatic scattering pattern calculated for the region circled for null data collection was significantly different than that for the two target aspects. The contact amplitudes reported for the region with no target were between 30 and 40dB lower than for the region approximating the location of the steel pipe. The variation in amplitudes was also much smaller.
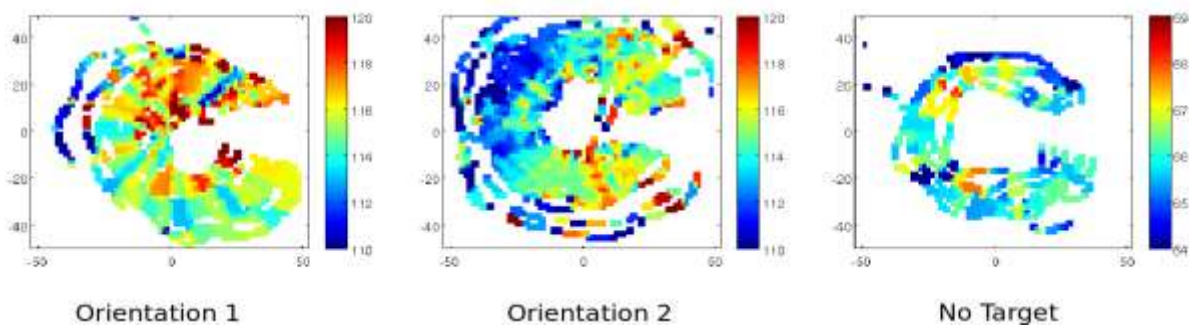

Figure G: Color plots showing scattering amplitudes collected around targets for orientations 1 and 2, and for null sampling with no target present.

Comparison to simulation

The true orientation of the steel pipe in the Massachusetts Bay Experiment was unknown during the experiment: the pipe was dropped off of the R/V *Resolution* without any rotation control. The orientation for each of the two target aspects was instead estimated using the cylinder orientation regression methodology described above. Orientation 1 was estimated as 110 degrees and orientation 2 as 35 degrees (Figure H). The difference between the two angles is consistent with the change in ship location between data collection on the two target aspects.
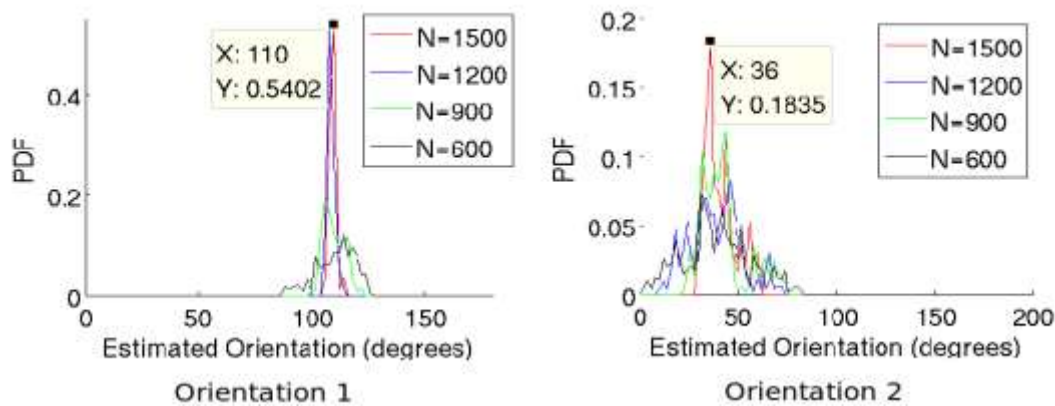

Figure H: Orientation estimates versus number of samples for both target aspects. SVM regression estimated the first orientation to have a target with an angle of 110 degrees, and the second to have an angle of 35 degrees.

The radiation pattern for both orientations, compared to fields for the simulated target with 35 degree and 110 degree angles, are shown in Figure I. The model's match to the real data is far closer for the orientation 1 than orientation 2. While the forward-scatter behavior of the scattering pattern diverged in both cases between the simulated closed-ended cylinder and the real, open-ended pipe, the general radiation pattern in the backscatter direction has common features. The simulated scattering fields were generated using a fluid-filled cylinder model, which is only an approximation to the scattered field from a steel open-ended cylindrical shell. The exact bottom type and depth for the experiment site were also unknown, as was the pitch of the target. However, the match between simulated and real data was clearly sufficiently close for a regression model trained on simulation data to be used to estimate the orientation of real data, even if a human might find it difficult to discern the angle of orientation 1 by eye.
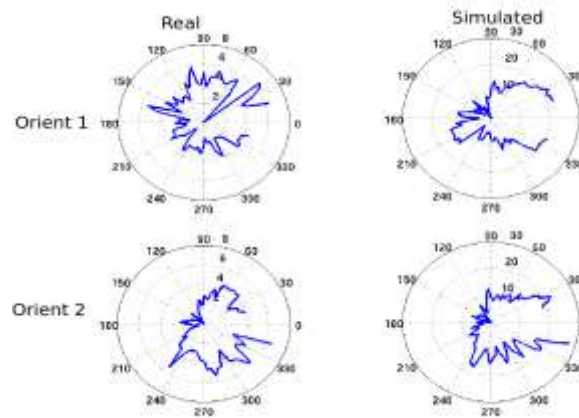
Figure I: Comparison of real versus simulated scattered fields for the two target aspects in the Massachusetts Bay experiment.

Conclusions

The Massachusetts Bay Experiment was an excellent test of the target characterization technique. The source location was uncertain as it was located on a ship swinging at anchor, with a software trigger that caused a 5ms jitter in firing time relative to the CSAC PPS reference. The acoustic source was omnidirectional, only 147dB, and at a reasonable distance from the targets (100 m). The actual target location and orientation were not known during the experiment as the steel pipe was dropped off the back of the ship and the position approximately estimated via GPS (the original estimates were 15-20m off of the final estimates). Only half the sonar aperture was available as the second DAB malfunctioned, so that only the first 8 channels were available for processing. Despite the challenges, the acoustic data collected during this test was excellent.

Training a SVM regression model on simulated scattered fields of cylinders of different orientations then estimating the orientation of the real pipe in the experiment was very successful. After 1400s of data collection, both orientations converged to a solution that was consistent with the change in ship position between aspects and with observed features in the scattering radiation pattern. This excellent performance was despite the fact that the simulation model was not a very good match for the experiment conditions and the fact that the scattering patterns for the 110 degree aspect do not look visually similar between real and simulated cases. The model is clearly able to pick out the important features in common, ignoring the details in scattering pattern that makes matching difficult, in this case, for a human observer. The influence of environment, target composition, bottom topography, and target geometry should be explored in future work, using simulation and real-world experiments. The success in estimation despite the differences between the model and real target geometry suggests that a similar method might be tried to estimate the orientation of a variety of aspect-dependent targets, including those with more complex geometries.

IMPACT/APPLICATIONS

The long-term impact of this effort is the development of new sonar concepts for MCM and ASW, which take optimum advantage of the mobility, autonomy and adaptation of an autonomous, cooperating vehicle network. For example, bi- and multi-static, low-frequency sonar configurations are being explored for completely or partially proud or buried mines in shallow water, with the traditional high-resolution acoustic imaging being replaced by a 3-D acoustic field characterization as a combined detection and classification paradigm, exploring spatial and temporal characteristics which uniquely define the target and the reverberation environment. Similarly, platform mobility and collaboration is being explored for enhancing DCLT performance of littoral surveillance networks such as PLUSNet, and deep water equivalents developed under the DARPA DSOP (now DASH) program, and most recently the DARPA FAST (Future Arctic Sensing Technologies) program.

TRANSITIONS

The GOATS'2014 program is a seamless continuation of the previous GOATS'2011 research effort. The progress made in autonomous, multi-AUV, net-centric control, navigation, communication, and collaborative sensing and its implementation into the open-source MOOS-IvP autonomy system architecture is being maintained and distributed by MIT-LAMSS under the GOATS Grant.

In 2010 the MOOS-IvP software architecture operated and distributed originally developed by P. Newman under GOATS funding in 2002) was been chosen at the platform autonomy system baseline for the DARPA Deep Sea Operations Program (DSOP), now in Phase 4 on a transition track under the name SHARK (Submarine Hold At RisK) Program, recently identified as one of 6 critical USN 'Spike' programs by the CNO. It has also been adopted as the basis for a major effort at the NATO CMRE on the development of autonomous, multi-static active sonar concepts under Program, as demonstrated in the GLINT'10 and '11 experiments with MIT involvement, and several more recent restricted CMRE field efforts. MOOS-IvP continues to be widely adopted worldwide, with the user community, now including renowned research institutions such as NURC (now CMRE), DRDC (Canada), DSTO (Australia), NSWC (Panama City), NUWC (Newport), NRL (DC), Georgia Tech, Auburn Univ., University of Oxford (UK), and JPL (Pasadena, CA). A wide range of US defense contractors have adopted it as well, most recently SSCI (Woburn, MA) and APS (Groton CT).

In 2014 MIT LAMSS were invited to participate in the COMSUBFOR ICEX16 experiment with our BF21 UUV with its towed array, with the scientific objective of characterizing the ambient noise environment in the rapidly changing Arctic. Subsequently through MIT-Lincoln Lab the

MIT UUV and towed array will be used in joint experiments with SUBDEVRON12, exploiting the chancing environment acoustics for Naval operations. This effort is funded separately by ONR Experimentation funds, and COMSUBFOR through the Arctic Submarine Lab.

At the core of the MIT LAMSS unified command and control infrastructure for heterogeneous undersea networks is acoustic communications software goby-acomms software [3]. This software infrastructure has begun to see substantial use outside the MIT community in the last couple of years. Outside of the MOOS community, Hanumant Singh's group at WHOI has been evaluating some of the Goby-Acomms modules for use on the Seabed vehicles. Within the MOOS community, groups at Georgia Tech Research Institute, CMRE, NAVSEA Panama City, the Naval Postgraduate School, and elsewhere are using Goby-Acomms with their autonomous vehicles.

The seismo-acoustic models developed by MIT are being maintained and disseminated under the GOATS grant. The OASES and CSNAP environmental acoustic modeling codes are used extensively in the ONR sponsored research at MIT, and continue to be maintained, expanded and made available to the community. The latest addition is a 3D version of CSNAP, which efficiently provides wave-theory solutions for propagation and scattering around seamounts. OASES and CSNAP is continuously being exported or downloaded from the OASES web site, and used extensively by the community as a reference model for ocean seismo acoustics in general. (http://acoustics.mit.edu/arctic0/henrik/www/oases.html)

RELATED PROJECTS

The Nested Autonomy architecture and acoustic modeling capabilities developed under GOATS has been applied in several other related programs MIT are partnering in, most notably the current DARPA DASH deep ocean active sonar program, where it is used as the core autonomy software infrastructure for adaptively controlling the platform and sonar operation, with several recent successful field demonstrations in 2013-14. In 2015, LAMSS was awarded a grant from DARPA under the Future Arctic Sensing Technologies (FAST) Program (John Kamp, Program Manager).

The continued development and maintenance of the MOOS-IvP autonomy software being funded by ONR Code 31 (D. Wagner and B. Kamger-Parsi, Program Managers), and is also supported by funding from non-Government Institutions such as the Battelle memorial Institute.

The MOOS-IvP autonomy software infrastructure developed and maintained partially under this grant was used by the MIT team participating in the ONR sponsored, International RobotX Competition, in Singapore in Oct. 2014.

The OASES modeling framework, which is being maintained, upgraded, and distributed to the community under this award, has been used intensively in all the related programs MIT is participating in, and a wide range of other ONR sponsored, fundamental and applied research programs.

PUBLICATIONS

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